Proceedings of the IPG 2023
6ª International Conference on Geotechnics de Ducts
ACIEM - ASME
November 23-24, 2023, Bogotá D.C., Colombia

IPG2023-0030

ESTIMATION OF MAXIMUM DAILY RAINFALL AS SUPPORT TO THE INTEGRAL MANAGEMENT OF THE THREAT DUE TO CLIMATE AND EXTERNAL FORCES IN TRANSPORTATION SYSTEMS

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ABSTRACT

Maximum daily rainfall can trigger landslide events and flash floods in natural currents, so it is of great interest to make a reliable estimation of the magnitude and frequency of these threats in hydrocarbon transportation systems (HTS). The case study is Oleoducto Central S.A., where daily extreme rainfall is estimated using traditional methods and projections to the year 2050 are proposed. The daily information available for Colombia is used, and a possible relationship between daily rainfall and altitude is sought. The analysis of trends by decades is carried out for some stations; extreme rainfall is estimated for the period 1991–2020; and the parameters of the probability distribution functions (PDF) are analyzed, looking for the best fit of the historical series to observe possible trends, and, if found, future values of maximum events are proposed for the year 2050. The results indicate that it is possible to propose an acceptable relationship between altitude and precipitation. The tendency analysis shows that there is no clear trend along the HTS. Extreme rainfall in some areas follows patterns that allow an estimation up to 2050. All this information is useful for decision-makers in comprehensive risk management, who can make use of the estimate of extreme rainfall to include it in landslide studies and flood analysis in those places where HTS crossed with the natural currents.

Keywords: Extreme Events, PMP, Maximum annual daily rainfall, non-stationarity.

1 INTRODUCTION

This article describes the process used to estimate the daily extreme rainfall events in the area of influence of the Hydrocarbon Transportation System (HTS) of "Oleoducto Central S.A." using the available recorded temporal series of daily rainfall in Colombia.

The estimation of daily maximum rainfall is of great interest for the evaluation of natural hazards and is carried out in multiple ways, where traditionally the use of classical statistical methods such as frequency analysis is recommended, but recently it is most frequent the use of indicators [1,2], as well as the classical method known as the Probable Maximum Precipitation (PMP) proposed by Herschfield [2].

In the literature, there are many spatial interpolation methods for estimating spatial distribution of rainfall; the most widely used are the isohyet method and Thiessen polygons, which are widely used for annual rainfall values and for rainfall events, respectively. The Inverse Distance Weight (IDW) and Ordinary Kriging (KO) methods are widely used in extreme rainfall events, with the IDW being the most recommended method since it does not require prior parameter estimation, as kriging does, and it is also reported that for the Colombian region, the results obtained are similar to each other [3,4,5], although it is recognized that each region must carry out its own study.

According to [6], rainfall is the most common landslide-triggering factor. Colombia show complex precipitation patterns with spatial-temporal variability and due to climate change the occurrence of catastrophic landslides events is expected to increase [7]. Therefore, in the study area of the HTS, a non-stationary analysis is carried out for the longest time series of extreme rainfall with the objective of understanding the influence of the change in land use and cover, the changes in magnitude and frequency of maximum daily rainfall in recent years; both aspects related to climate change. Therefore, different strategies allow an estimation of maximum daily rainfall [8, 9]. For this study, the series with more than 50 years of data is selected, and through a tendency analysis of the 30-year time window, moving it every 5 years; if trends are detected, then it can be considered evidence or indications of a change in the extreme events data, and at that point using trends to carry out projections to the year 2050 can be performed.

The objective of the aforementioned activities is to improve the comprehension and understanding of the maximum daily rainfall that can be recorded in one day in the study area of the HTS, and its future trend as an integral management element of the threat, hazard, and risk due to weather and external forces in the influence area of Oleoducto Central S.A. So, the research question is: What would be the maximum daily rainfall that occurs along the HTS? Under the assumption that higher maximum daily rainfall increases landslide occurrence and support to the integral management of the threat due to climate and external forces.

2 MATERIALS AND METHODS

The proposed methodology is based on sequential activities, which allow for obtaining an idea of the spatial variability, frequency, and magnitude of the maximum daily rainfall in the study area. This methodology is briefly described in Figure 1.

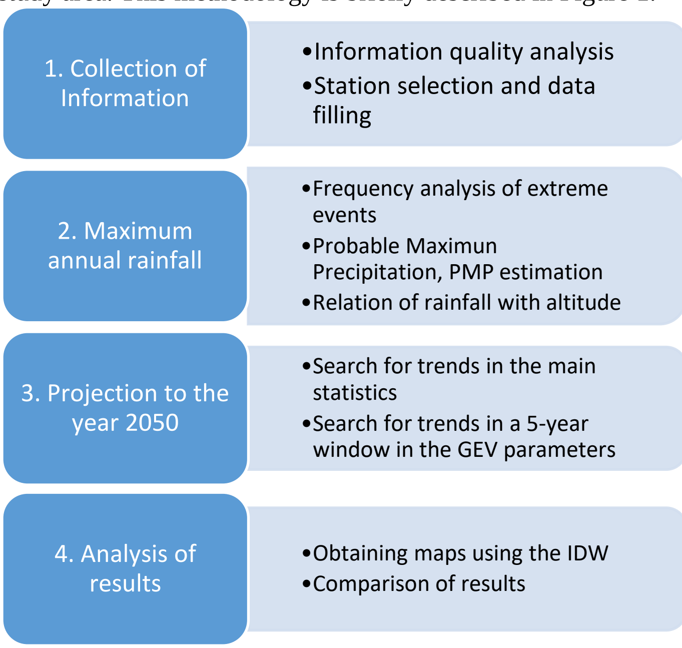

FIGURE 1: SCHEME OF THE PROPOSED METHODOLOGY.

The official entity in charge of providing climatic information at the national scale in Colombia is the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, in Spanish), so the information available on daily rainfall was sought at IDEAM´s stations with 30 years of data or more in the area of influence of HTS. The location of the IDEAM stations with information on rainfall is shown in Figure 2, where the topography, the pipeline (black line), and the area of influence (width of 25 km) are superimposed. Although an acceptable spatial distribution of gauge stations is observed along the pipeline, there are sections where the monitoring of rainfall is scarce.

Different authors [10,11] have determined that the remote sensing information from the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station) reanalysis is the option with the best performance among different sources of remote sensing available for free on the World Wide Web for the Colombian Andean zone. Therefore, it is proposed to use the relationship between the data accumulated by IDEAM and the collected data from CHIRPS as a tool for gap-filling missing data. The IDEAM data are point data that are recorded at each one of the stations. They are obviously different from the CHIRPS data, whose records come from an aerial estimate of 5.5 km x 5.5 km. Still, CHIRPS data can serve as a reference to complete IDEAM data if the adjustment factor that relates both sources of information is previously estimated and used.

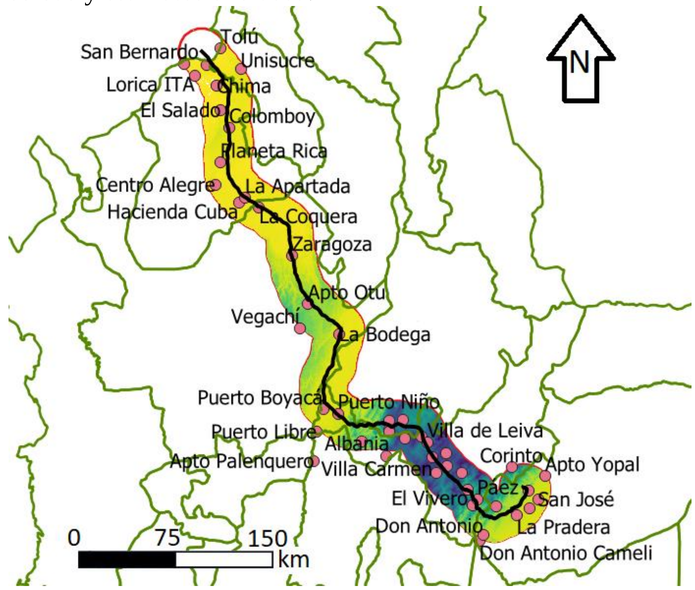

FIGURE 2: ZONE OF INFLUENCE FOR THE STUDY AND LOCATION OF THE IDEAM STATIONS.

The estimation of maximum daily annual rainfall is carried out using the classical Probable Maximum Precipitation (PMP) methodology [2], and it is compared with the estimation made with the traditional frequency analysis for a period of return of 1000 years.

Subsequently, projections to the year 2050 are proposed using a moving window every 5 years with 50-year data series, both for the main statistics and for the parameters of the Probability Distribution Functions (PDF), and both methodologies are compared for the HTS study area.

The spatial distribution of rainfall in Colombia varies strongly, and for spatial interpolation, the Inverse Distance Weighting (IDW) method is adopted, which is a type of deterministic method for multivariate interpolation with a known scattered set of points. IDW method does not require additional parameter estimation and shows good behavior for the Colombian area [3,4,5].

Finally, the comparison and analysis of the results presented with the main conclusions is made.

3 RESULTS AND DISCUSSION

The main results are presented below, where only the results for some stations are presented, but the analysis has been carried out for all the selected stations.

3.1 Collection of information

The daily rainfall information collected from IDEAM is used for the stations in the area of influence of the HTS of Oleoducto Central S.A. A review of the maximum daily annual data is carried out for all the IDEAM stations, which indicate that there is no common year in which the maximum event occurs. For all data series, a consistency and homogeneity analysis is performed.

The maximum annual rainfall data series show high spatial and temporal variability of extreme rainfall in the area of influence of the HTS. Figure 3 shows the box and whisker diagram for the selected stations, where this variability in rainfall is observed along the study area.

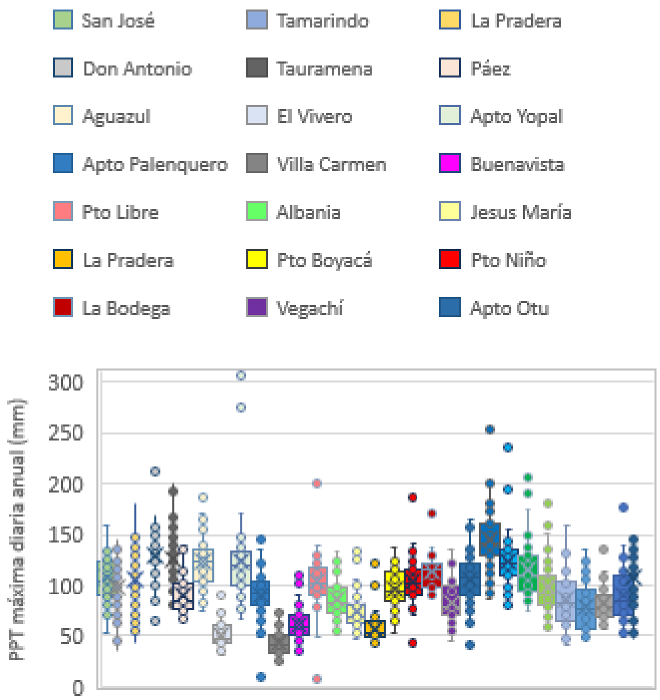

FIGURE 3: DIAGRAM OF BOX AND WHISKERS FOR THE SERIES OF MAXIMUM DAILY RAINFALL IN THE HTS.

Figure 4 shows the frequency histogram for all the maximum daily annual rainfall recorded in the area, where values greater than 300 mm only occur once in the entire area, there are five values between 200 mm and 300 mm, and the highest frequency of values is observed for the range between 50 mm and 100 mm, followed by the range between 100 mm and 150 mm. Additionally, when the frequency histograms at the stations are analyzed individually, in all cases the bias to the left is observed, which is typical of extreme values.

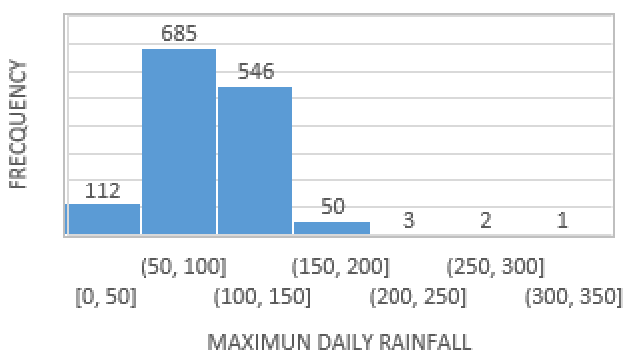

FIGURE 4: FREQUENCY HISTOGRAM OF MAXIMUM DAILY RAINFALL FOR ALL IDEAM STATIONS.

The analysis of the frequency of extreme events is carried out with the maximum daily annual information from the IDEAM stations located in the area of influence, the maximum daily rainfall of each year is selected and with it the main statistics are estimated, such as the average, standard deviation, bias and kurtosis, at each station. The mean maximum daily rainfall values, for all selected stations, oscillate between 42.9 mm and 145.8 mm, with a standard deviation between 11.7 mm and 31 mm, indicating a high variability in the HTS area. It is important to mention that the Yopal Airport, Zaragoza, La Coquera, La Apartada, Tauramena and Puerto Libre stations present maximum daily annual values greater than 200 mm, for which reason a consistency analysis of the information was necessary to detect values doubtful The nearby stations are reviewed to see if the registered values are coherent with the expected reality, in this way the double mass analysis and the Mann-Kendall trend test are carried out, to determine if the doubtful values can really be part of the of the historical record, in the few cases in which realistic values are not considered, such as the case of the Yopal Airport that registers a value of 305.6 mm on 04/27/2020, but observed the temporal series, this value must be the cumulative value since 20/03/2020, because before this date there are no records, so it must be an erroneous value with a lot of uncertainty due to lack of data, and its elimination is proceeded. Additionally, under the premise of errors in the transmission, transcription or failures in the measurement device some outliers' values are removed.

However, most of the values available in the IDEAM database were correctly recorded in the study, considering that there is a range of values that suggest the possibility of a real record for values greater than 150 to 300 mm, based on the knowledge of the climate and high variability present in the area, where it is feasible with a very low probability that these values of maximum daily rainfall occur, due to very localized storms presumably of convective origin.

3.2 Frequency analysis of extreme events

The analysis of extreme events refers to the statistical analysis that uses the frequency of a historical series to fit a Probability Distribution Function (PDF) that allows the estimation of events with a low probability of occurrence.

We proceed to verify the best fit among different Probability Distribution Function as: Gumbel, Log-Normal, General Extreme Value GEV and Two Component Extreme Value, TCEV. The results of the comparison indicate that GEV distribution show the best fit for all IDEAM stations. As an example, Table 1 shows for the period of return of a thousand years (Tr=1000 years), the extreme values with a probability of 0.001 vary between 119.2 mm and 362.7 mm, which gives an idea of the order of magnitude expected by the pluviometers and pluviographs in the study area.

Some of the graphic results of the frequency analysis of daily extreme events are presented in Figure 5. The analysis requires observing the slopes of the adjustments and their concavity, to detect whether the proposed results underestimate or overestimate the most extreme events. In the case of Planeta

Rica, a good fit is observed and the tendency indicate high values at the extremes events; the opposite case is observed in Buenavista station, where due to the slope the fit indicate a tendency to estimate lower extreme events. Regarding the upward concavity (positive), the Tamarindo station show that the extreme values tend towards a constant value with a moderate increase in extreme values, and La Apartada and La Pradera stations are an example of the downward concavity (negative), indicating that the extreme values tend to increase significantly in the extreme values; in the case of La Apartada, a value of 320 mm/day is estimated for a return period of 1000 years. Finally, in the case of the Yopal Airport, a daily maximum historical value of 274.6 mm/day is observed on May 2, 2011, a date that coincides with rainy periods in Colombia, both due to the ZCIT and the cold phase of the ENSO (La Niña); in this case, the results are barely acceptable for the GEV distribution, but the estimated rainfall for a return period of 1000 years, 248.7 mm/day, is even less than the recorded rainfall.

TABLE 1: RESULTS OF THE FREQUENCY ANALYSIS (GEV) FOR A RETURN PERIOD OF 1000 YEARS.

Station	Tr=1000	Station	Tr=1000
San José	163.8	Pto Niño	186.8
Tamarindo	146.5	La Bodega	197.4
La Pradera	187	Vegachí	152.2
Don Antonio	222.8	Albania	203.4
Tauramena	240.4	Apto Otu	168.9
Páez	213.3	Zaragoza	260.9
Aguazul	200.6	La Coquera	251.8
El Vivero	123.1	La Apartada	320.8
Apto Yopal	276.6	Planeta Rica	248.7
Apto Palenquero	147.4	Colomboy	192.5
Villa Carmen	119.2	Lorica ITA	201.7
Buenavista	134.6	Unisucre	216.6
Pto Libre	140.9	Villa Marcela	246.7
Albania	167.4	Tolú	153
Jesus María	171.7	La Esperanza	80.6
La Pradera	155.5	Agronomía	183
Pto Boyacá	146.4	Apto La Nubia	194.3

The presence of both concavities in the GEV distribution, and the variable slopes of the adjustment curves, indicate the high variability of maximum daily rainfall in the area, without an identifiable spatial pattern for the region.

Figure 6 shows the spatial distribution for rainfall with a period of return of 1000 years, it is obtained by interpolation with the IDW using the estimate in the stations located in the area of influence. For this reason, the results of the spatial variability are valid only for the area of influence.

It is essential to highlight that the frequency analysis of extreme events was carried out in order to obtain probable daily maximum values of rainfall: Almost all the extreme values available in the IDEAM database were used, and it was not recommended to remove some data from the analysis of the historical data, since these are values that, although they are apparently "outliers", and cannot be contrasted with nearby stations or with satellite records, these outliers have a small probability of occurrence due to its natural complex process. This behavior can be explained physically due to the geographical location and given the atmospheric conditions of the tropical area of the Eastern Cordillera and the Colombian Magdalena valley, these are places where the jet currents of the Caribbean and Chocó converge with the humidity of the Amazon Forest [12, 13, 14, 15], which make possible the occurrence of these extreme events with a very low probability.

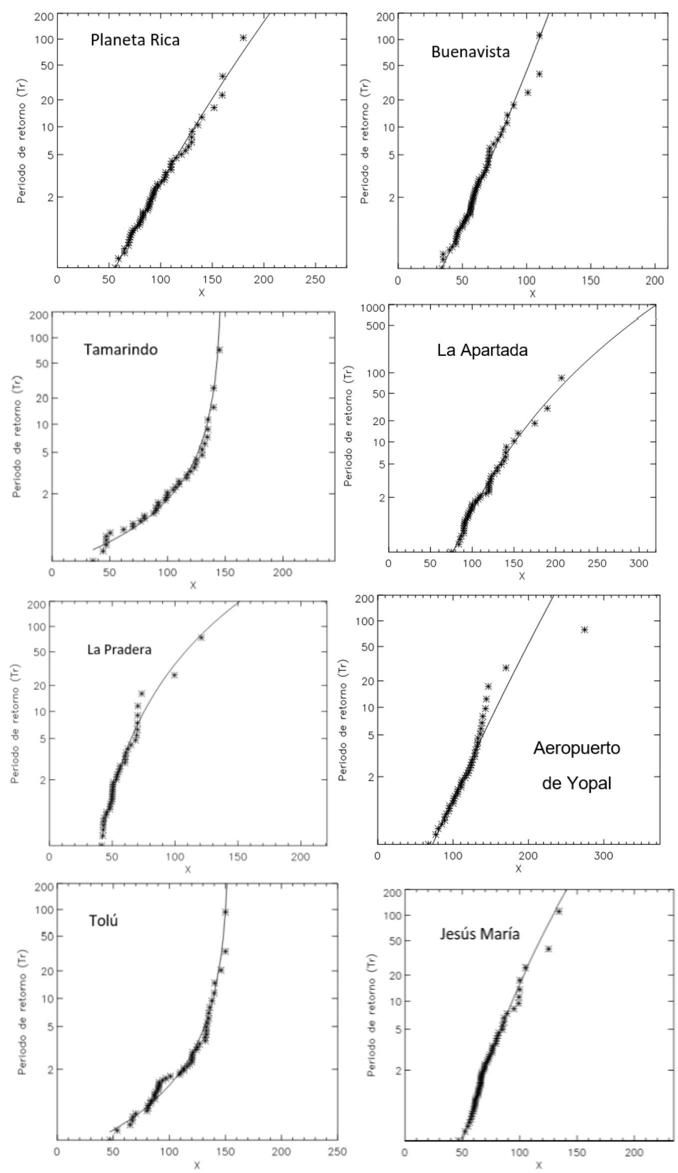

FIGURE 5: SOME RESULTS OF THE GEV DISTRIBUTION PERFORMED AT IDEAM'S STATIONS.

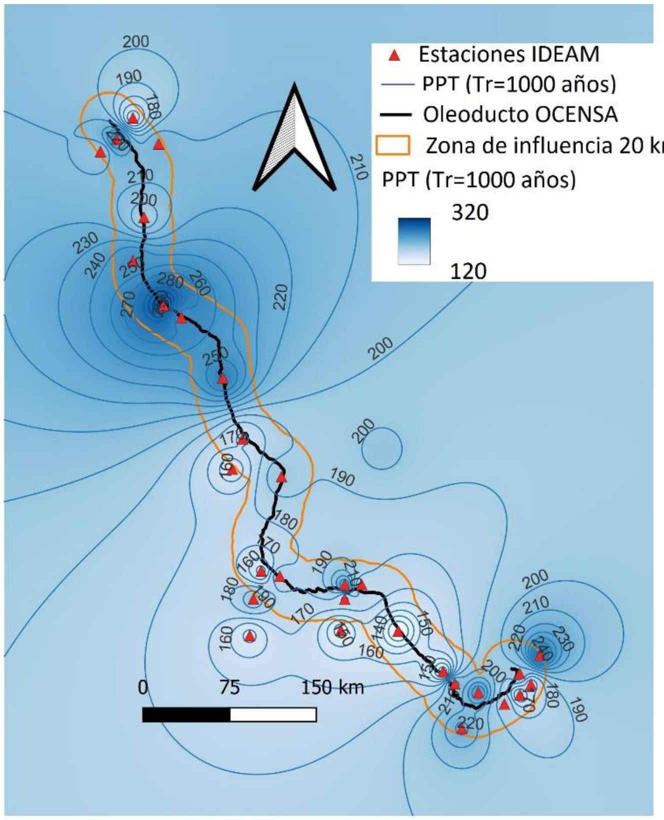

FIGURE 6: SPATIAL DISTRIBUTION OF MAXIMUM DAILY RAINFALL FOR TR=1000 YEARS.

3.3 Probable Maximum Precipitation, PMP estimation

In order to answer the question of the maximum daily values that occur in a given place, the concept of Probable Maximum Precipitation (PMP) proposed by Hershfield [2] can be used in its version adapted for regional studies, who proposes the following equations:

$$PMP = X_n + k_m \cdot \sigma_n \quad (1)$$

$$k_m = \frac{X_{max} - X_{n-1}}{\sigma_{n-1}} \quad (2)$$

Where, X_n is the mean value of the annual maximum daily rainfall (mm), σ_n is the standard deviation of the annual maximum daily rainfall, k_m is the frequency factor, X_{max} is the maximum rainfall observed in the entire historical record and X_{n-1} is the average of the series after excluding X_{max}, and σ_{n-1} is the standard deviation of the annual maximum daily rainfall after excluding X_{max}.

Subsequently, the graph k_m *vs.* X_n is obtained to determine the envelope curve of the extreme points by means of the best fit equation of the maximum points. The best fit in the area was a logarithmic function, which is adequate as the envelope for the four orange points, as can be seen in the Figure 7, where the envelope curve found excludes the values of the Yopal Airport and La Coquera stations, so that it is because a descending envelope must be proposed according to the proposed method, in this way the PMP values at these stations will be lower.

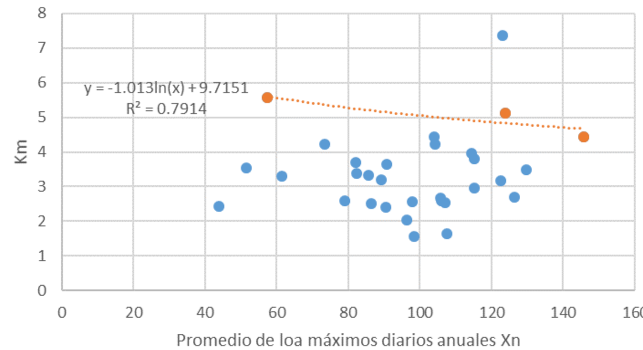

FIGURE 7: K_M AND X_N PARAMETERS FOR PMP ADJUSTMENT (DASHED LINE).

After the estimation of the envelope curve (logarithm fit), it is necessary to proceed to estimate the PMP, the results obtained for the HTS are presented in Table 2, where the PMP is proposed as a reference value for the maximum daily rainfall, although it is estimated that the occurrence of the PMP has a very low probability and is not expected to occur, the results are observed in a range of values between 122 mm and 337 mm.

TABLE 2: RESULTS OF THE ESTIMATION OF THE PMP.

Station	Max PPT (mm)	km	log Xn	km (ajust.)	PMP
San José	158	2.549	2.03	5.162	219
Tamarindo	145	1.558	1.993	5.251	262
La Pradera	180	2.675	2.024	5.176	263
Don Antonio	211	3.485	2.113	4.932	273
Tauramena	200	2.703	2.102	4.966	275
Páez	139.5	3.201	1.95	5.349	184
Aguazul	187	3.175	2.089	5.003	237
El Vivero	90.4	3.53	1.713	5.767	126
Apto Yopal	306	5.752	2.091	4.997	337
Apto Palenquero	144.3	2.398	1.956	5.336	219
Villa Carmen	74.3	2.435	1.644	5.855	122
Buenavista	110	3.302	1.788	5.656	153
Pto Libre	200	4.233	2.018	5.191	244
Albania	133	2.523	1.936	5.38	194
Jesus María	134.2	4.224	1.866	5.52	164
La Pradera S	120.9	5.565	1.759	5.701	145
Pto Boyacá	137	2.028	1.984	5.272	202
Pto Niño	186	4.43	2.017	5.194	220
La Bodega	170	3.963	2.059	5.086	208
Vegachí	136	3.391	1.916	5.423	180
Apto Otu	165	2.589	2.026	5.171	230
Zaragoza	253	4.438	2.164	4.777	283
La Coquera	235	5.113	2.093	4.99	266
La Apartada	207	3.81	2.061	5.078	257
Planeta Rica	160	2.562	1.991	5.256	239
Colomboy	158.4	3.325	1.932	5.388	219
Lorica ITA	135	2.601	1.898	5.459	207
Unisucre	141.4	3.696	1.915	5.425	186
Villa Marcela	177	3.654	1.958	5.332	244
Tolú	150	1.649	2.032	5.156	245

Figure 8 shows the spatial distribution, estimated using the IDW, for the PMP (mm/day) in the area of influence of the HTS of Oleoducto Central S.A.

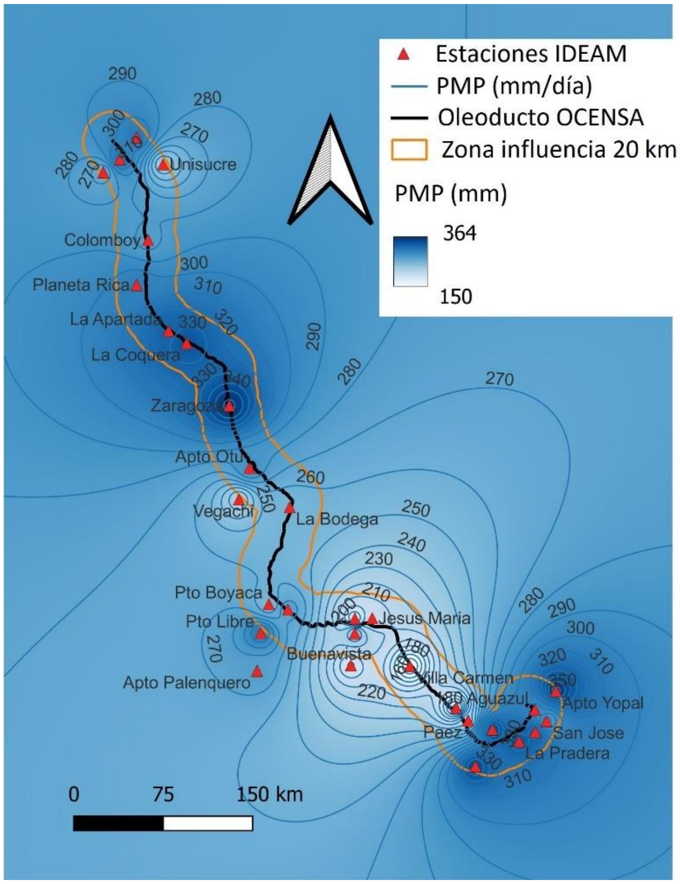

FIGURE 8: SPATIAL DISTRIBUTION OF PMP (MM/DAY) IN THE AREA OF INFLUENCE OF THE HTS

Although it is considered that the PMP is a good approximation to determine the maximum daily precipitation events in a region, it is proposed to explore if there is a good relationship between the altitude and the extreme events of registered maximum daily rainfall and values estimated using the frequency analysis with low probabilities, these results are presented below.

3.4 Relation of rainfall with altitude

The existence of a relationship between rainfall and altitude allows for a better estimation of the spatial variability of the maximum daily rainfall fields. Figure 9 (top) shows the relationship between altitude and the average value of annual daily maximum values for all stations during the period 1990-2019, and Figure 9 (bottom) presents the relationship between altitude and standard deviation. of the annual daily maximum values for all seasons for the same period. Both graphs present a negative trend, which indicates in the average value that in general the maximum daily annual rainfall tends to be less in the highest areas, and the error or dispersion indicated by the standard deviation also shows a decrease with elevation. This is important because it indicates that there are orographic effects in the maximum daily annual rainfall; where it rains more, there is also greater dispersion or error in the measurement.

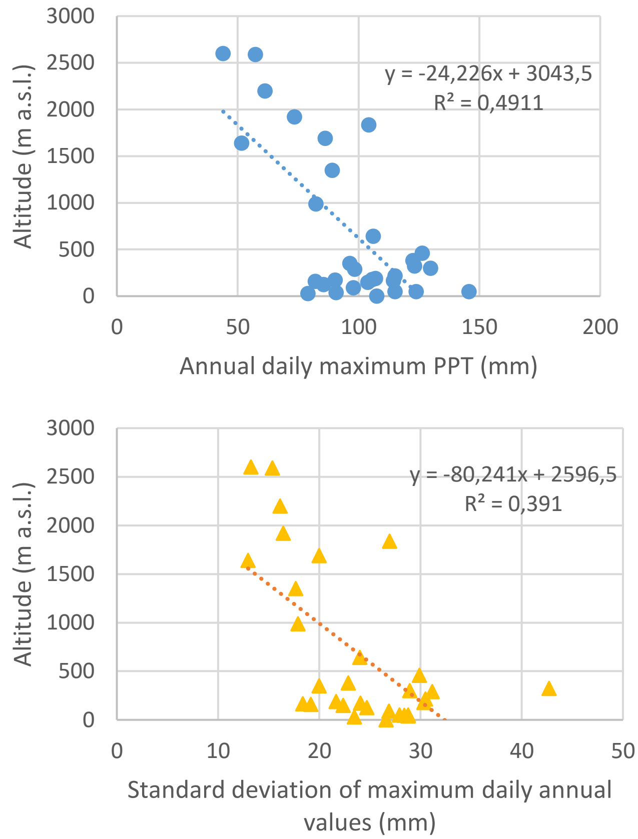

FIGURE 9: ALTITUDE VS MEAN ANNUAL RAINFALL (UP) AND ALTITUDE VS STANDARD DEVIATION (BELOW).

Another way to address the question about the maximum possible values of daily rainfall in the study area is to verify the existence of a relationship between altitude and rainfall for a period of return of 1000 years (Tr=1000 years), and although it is not evident a correlation between the maximum daily rainfall and the elevation, it can be seen in Figure 10 that according to the frequency analysis results, apparently there is a decrease with the elevation for the GEV distribution with a Tr=1000 years. The same graph shows the envelope curve (continuous red line) for the relationship between altitude and extreme rainfall Tr=1000 years. If La Pradera station is eliminated, it can be approximated to a single line (dotted orange line), these envelopes curves can be understood as a reference for the maximum possible daily rainfall events that are feasible in a place in the area of influence of the oil pipeline, with probability of 0.001, using only its altitude. For purposes of the area of influence of the HTS, it is proposed to use the information from all the stations, that is, the solid red line.

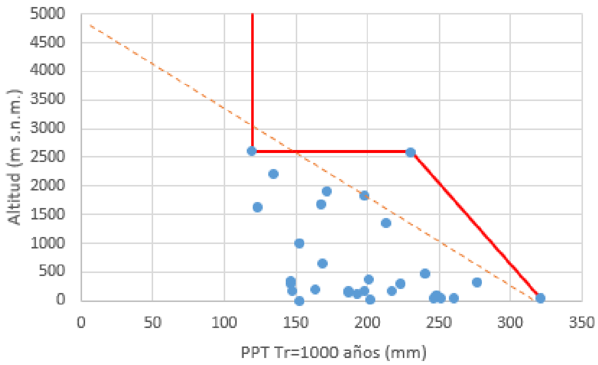

FIGURE 10: ALTITUDE RELATIONSHIP VS. MAXIMUM RAINFALL (TR=1000 YEARS), THE RED LINE IS THE ENVELOPE AND THE ORANGE (DOT) IS THE ENVELOPE THAT EXCLUDES LA PRADERA STATION.

Additionally, it is possible to use the altitude from the Digital Elevation Model (DEM) aggregated to a resolution of 1 km x 1 km to estimate the terrain profile along the pipeline. Figure 11 show in the same graph, the comparison of the maximum possible daily rainfall with probability of 0.001 (Tr=1000 years), the estimated value of PMP, and the envelope curve. The results indicate that the first approach of the envelope curve using PMP overestimates a large part of the maximum daily values, therefore a lower estimation is requested, then, a proportion of the PMP is recommended, the suggestion of the authors is 85 percent of the PMP as a value closest to reality, and it is proposed as the maximum value for a daily precipitation in the study area of HTS, because it has a very low occurrence probability, varies with the altitude and it is not as extreme as the PMP.

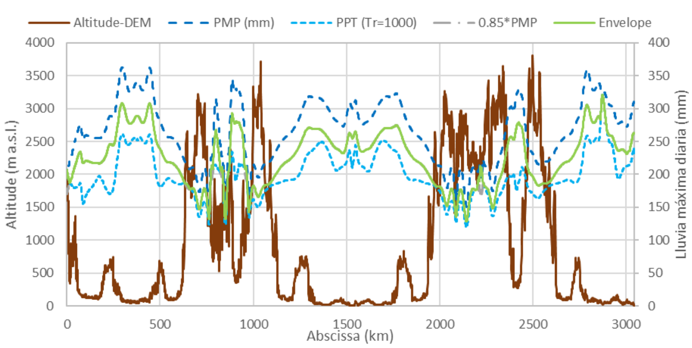

FIGURE 11: COMPARISON ALONG THE ALTITUDINAL PROFILE AMONG THE OIL PIPELINE WITH THE MAXIMUM DAILY RAINFALL ESTIMATED ACCORDING TO PMP, TR=1000 YEARS AND ENVELOPE CURVE.

The maximum daily annual values do not follow clear correlations with the elevation or the terrain profile, it is estimated that the extreme events are variable, isolated and very strong, since no regional patterns are observed in these daily rains since there is no evidence of similar events in the nearby stations, nor in the satellite records that tend to moderate the extreme values due to their spatial scale. Additionally, the distance between stations means that the spatial variability of extreme daily rainfall events is not adequately captured, indicating the need to improve rainfall monitoring along the HTS.

3.5 Projection to the year 2050

Since long-time series of temperature and rainfall are not available, it is not possible to carry out a rigorous analysis of climate change for the area of influence of the HTS. Therefore, a tendency analysis is proposed for the extreme events of maximum annual daily rainfall, which may be an indicator of climate change effects [16, 17]. This analysis is carried out considering the climatic standard proposed by the World Meteorological Organization (WMO), which considers 30 consecutive years as the climatic normal [18]. Then, the proposed strategy is: 1) to observe the trends in the main statistics of long-time series (mean and standard deviation) for groups of 30 years of data spaced in a moving window of every 5 years; and 2) to detect a tendency in the parameters of the GEV distribution using a 5-year moving window of 30 years of data. However, this type of analysis can only be carried out at stations that have more than 50 years of data. Additionally, the Yopal Airport station is included in the analysis for information purposes because it shows outlier extreme values, so it is noted that the results on this site present greater uncertainty since it does not meet the requirement of having more than 50 years of data.

As an example, Table 3 shows the results of the analysis at the Buenavista station, but similar results are obtained for the other stations selected for this analysis.

TABLE 3: RESULTS OF THE FREQUENCY ANALYSIS (PDF GEV) FOR 30-YEAR PERIODS WITH A 5-YEAR MOVING WINDOW AT THE BUENAVISTA STATION

Time range	Period of return, Tr (years)						
	5	10	25	50	100	500	1000
1958-2019	73.2	82.3	93.5	101.7	109.6	127.2	134.6
1958-1988	73.4	84.5	99	110.2	121.6	149.3	161.8
1964-1994	75.6	86.3	100.1	110.4	120.7	144.9	155.4
1969-1999	74.7	85	98.5	109	119.7	146	157.9
1974-2004	70.1	79.6	92.9	103.9	115.8	147.6	163.4
1979-2009	71.5	79	87.7	93.5	99	110.1	114.3
1984-2014	73.5	81.9	91.9	98.9	105.6	119.8	125.5
1989-2019	72.6	80.2	89.4	95.8	101.9	115.1	120.3

Figure 12 shows the comparison of the trends in the main statistics (mean and standard deviation) obtained from the 30-year intervals with their 5-year moving window, where the year indicated in the graph corresponds to last year of the 30-year interval.

The IPCC report [16,17] for the Andean zone highlights that, although an increase in the variance of extreme events is expected, e.g., that extreme events are even more extreme, in the Andean zone this pattern may be variable, due to the microclimates that are generated in the inter-Andean valleys and in the highland plains.

This increase in the standard deviation through the 5-year moving window is confirmed for the Villa Carmen, Otu Airport, Zaragoza and Yopal Airport stations, and a decrease in the standard deviation is observed at the Jesús María, Planeta Rica and Tolu. There is not a clear pattern along the HTS.

Regarding the average annual maximum daily rainfall, an increase is observed in the five-year periods at the Yopal Airport, Tolú, Zaragoza, Jesús María, Otu Airport and Villa Carmen stations, and a decrease in the maximum annual rainfall is observed in Buenavista and Planeta Rica stations.

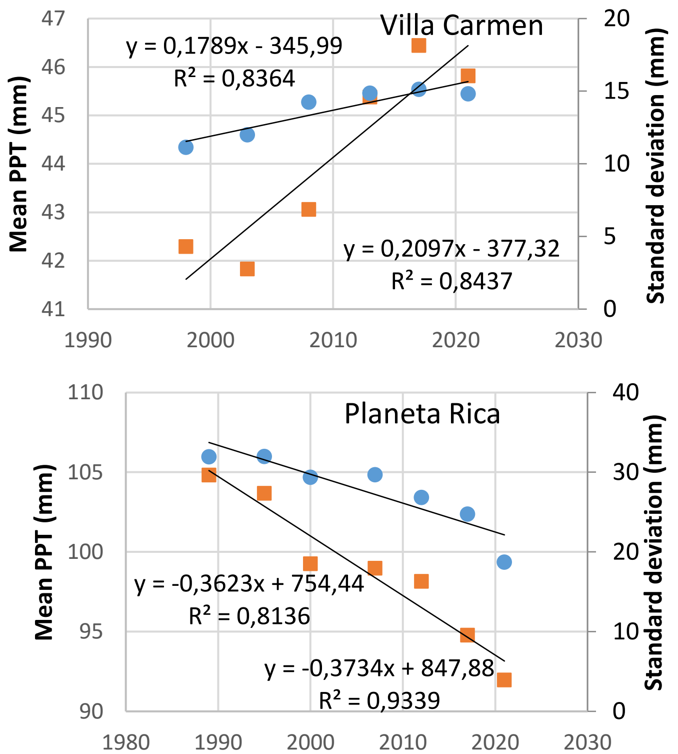

FIGURE 12: VARIATION OF THE MAIN STATISTICS OF THE MAXIMUM DAILY ANNUAL RAINFALL AT THE VILLA CARMEN STATION (ABOVE) AND PLANETA RICA STATION (BELOW). IN BLUE THE MEAN VALUES AND ORANGE THE STANDARD DEVIATION.

The results of the frequency analysis in the different stations using the 30-year periods with a 5-year moving window, allows observing the trends followed by the maximum daily annual rainfall in its different periods of return. The previously selected PDF GEV was used in all stations. The frequency analysis results for a period of return of 100 years and their linear adjustments are shown in Figure 13, it is highlighted that the trends are graphically extrapolated up to the year 2050, and the results show an increasing trend in Villa Carmen, Apto Otu, Zaragoza, Tolú and Yopal Airport stations, there is no clear trend in Jesús María and it is decreasing trend in Buenavista and Planeta Rica stations. In other words, there is not a single consistent pattern throughout the pipeline, but can be identified different tendencies by sectors.

The first results for the year 2050 allow us to conclude that these values can be estimated from time series data of 30 years in length with a 5-years moving windows, as can be seen in Table 4, where the results extrapolated to 2050 based on observed trends in each period of return is presented.

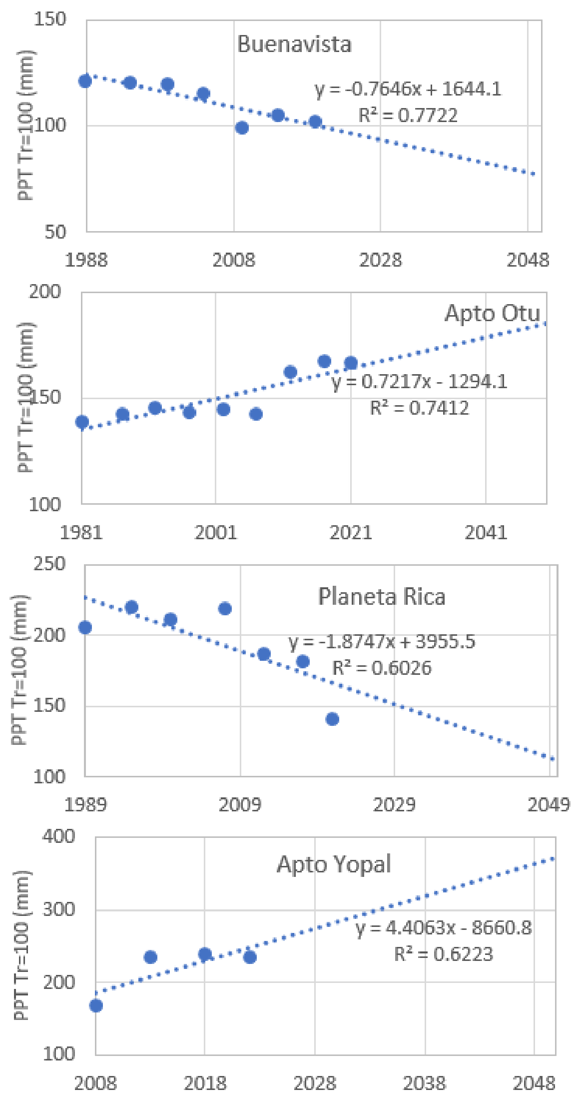

FIGURE 13: VARIATION OF THE ANNUAL MAXIMUM DAILY RAINFALL (TR=100 YEARS) ACCORDING TO THE VARIATION OBSERVED IN THE MOBILE WINDOW.

The second proposed way to view these trends is to look for relationships among the GEV parameters in a series of 30 years of data with a 5-year mobile window. In general, if trends are detected in the parameters of scale, shape, and location of the GEV distribution of the annual maximum daily rainfall data, it is possible to extrapolate the parameters to estimate extreme rainfall events in future periods using extrapolated parameters. In this way, an approximation of future variability can be made, which has been associated with climate change. Then, it is possible to estimate the extreme events of annual maximum daily precipitation in the year 2050, as an example.

TABLE 4: RESULTS OF THE EXTRAPOLATION TO 2050 OF MAXIMUM DAILY ANNUAL RAINFALL FOR DIFFERENT PERIODS OF RETURN

Station	Period of return, Tr (years)					
	5	25	50	100	500	1000
Villa Carmen	65.6	104.2	123.7	145.2	203.2	232
Buenavista	69.9	76.2	77	76.8	72.7	69.5
Jesus María	78.8	108.4	123.7	140.9	190.9	217.9
Apto Otu	136	166	176.3	185.3	201.9	207.5
Zaragoza	178	228.2	250.7	273.7	329.1	353.8
Planeta Rica	91	103.3	107.9	112.4	122.7	127.4
Tolú	122	127	127	126.7	125.8	125.6
Apto Yopal	182	277.8	323.6	372.1	495.5	552.9

Figure 14 shows the results of the analysis for the shape, scale, and location parameters (α, β y x_0) at the Buenavista station. Similar analyses were performed at all stations. The Buenavista, Planeta Rica, Yopal Airport, and Tolú stations show a trend in their parameters. Once the existence of trends in the GEV parameters has been detected, it is possible to perform extrapolations, and in this way, it is possible to estimate future values of the GEV parameters and observe the influence of recent changes in the data series.

The results of the extrapolation for the extreme events of annual maximum daily rainfall in the year 2050 are presented in Table 5, where the results for different return periods can be seen, corresponding to the results for the GEV distribution with the extrapolated parameters, The Tolú station is not included since it yields stable values around 127 m/day for periods of return greater than 50 years. In general, it is observed that the Buenavista and Planeta Rica stations are the ones that show a decrease in rainfall and Villa Carmen and Zaragoza show a very important increment.

4 CONCLUSIONS

Using only the IDEAM rainfall series guarantees homogeneity, but given that this is poor coverage for the entire HTS, the results are approximate and are a first approach. Rainfall monitoring at different elevations must be implemented to improve the relationship selected in this study.

The analysis of the maximum annual rainfall frequency indicated that, for all the selected stations, the best PDF was consistently the GEV distribution. Three different patterns were identified in the curvature of the GEV distribution, which confirms a strong variability of extreme daily rainfall in the area of influence of the HTS of Oleoducto Central S.A.

The spatial patterns observed for the maximum daily annual rainfall estimated with the PMP methodology and the frequency analysis for a period of return of 1000 years show the possible range of variation of extreme rainfall in the HTS region. Patterns consistent with altitude in the study area are also presented.

The non-stationary analysis of the maximum daily rainfall with a 5-year moving window is carried out satisfactorily for the 7 stations with records longer than 50 years; changes in the mean and in the variance were observed in all the stations. Although a regional pattern is not identified, mainly because there are so few stations, some stations show an increase in the amount of rain and others a decrease, confirming the variability both in the mean values and in the standard deviation. These aspects suggest changes in land use and land cover, which are effects associated with climate change and have already been mentioned in the IPCC [16,19].

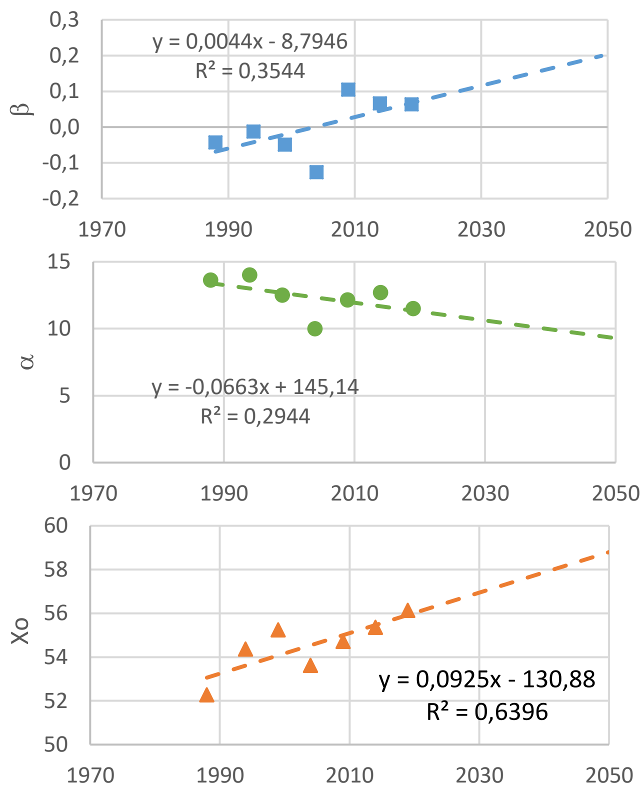

FIGURE 14: EXTRAPOLATION OF PARAMETERS OF THE PDF GEV AT THE BUENAVISTA STATION UP TO THE YEAR 2050.

TABLE 5: ESTIMATE OF MAXIMUM DAILY RAINFALL (MM/DAY) FOR DIFFERENT RETURN PERIODS IN THE YEAR 2050, USING PARAMETERS EXTRAPOLATED FROM GEV DISTRIBUTION

Estación	Período de retorno, Tr (años)					
	10	50	100	200	500	1000
Villa Carmen	87	152	193.2	245	335.1	424.8
Buenavista	75.6	83.8	86.6	88.9	91.6	93.3
Jesús María	91.1	124	141.5	160.8	190.2	215.8
Apto Otu	152	186	200.2	214.3	232.6	246.3
Zaragoza	201	258	285.4	314.9	357.5	392.7
Planeta Rica	97.8	110	115.2	119.8	125.5	129.5
Apto Yopal	257	493	655.9	875.9	1289	1731

In conclusion, it can be seen that there are differences in the estimates of the maximum daily annual rainfall if the methodology of direct extrapolation of the main statistics of maximum rainfall is used (Table 3), with respect to the values obtained with the extrapolation of the GEV parameters (Table 4). It should be noted that in the Buenavista and Villa Carmen stations, values are more adjusted to the observations with the approximation of the direct extrapolation of the main statistics, since much larger values are observed than the PMP when the approximation of the GEV parameters is used. There are also differences in the Yopal Airport station, but this temporal series is short, and the results may be due to this lack of data. The Jesús María, Otu Airport, Zaragoza, Planeta Rica and Tolú stations present estimates for the year 2050 that are very similar to each other.

In general, it is concluded that the maximum daily annual rainfall will increase by the year 2050 in some regions and decrease in others, so additional studies are required to be able to regionalize the area of influence of the Central Oleoduct's HTS in a more precise and consistent manner, including climate variability effects. All these knowledges related to maximum daily annual rainfall will increase the comprehension of landslide occurrence and will improve the integral management of the threat due to climate and external forces.

5 ACKNOWLEDGMENTS

The authors want to thank the Faculty of Engineering and Architecture of the National University of Colombia and Oleoducto Central S.A., who through Agreement 3803429 allow obtaining this type of research results.

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